High Capacity Wireless Communication Using Spatial Subchannels

RELATED APPLICATIONS

This application claims priority from U.S. provisional applications 60/025,227 and 60/025,228, both filed 08/29/96. Both applications are hereby incorporated by reference.

FIELD OF THE INVENTION

This invention relates generally to digital wireless communication systems. More particularly, it relates to using antenna arrays by both a base station and a subscriber to significantly increase the capacity of wireless communication systems.

BACKGROUND OF THE INVENTION

Due to the increasing demand for wireless communication, it has become necessary to develop techniques for more efficiently using the allocated frequency bands, i.e. increasing the capacity to communicate information within a limited available bandwidth. This increased capacity can be used to enhance system performance by increasing the number of information channels, by increasing the channel information rates and/or by increasing the channel reliability.

FIG. 1 shows a conventional low capacity wireless communication system. Information is transmitted from a base station B to subscribers $S_1, \ldots, S_9$ by broadcasting omnidirectional signals on one of several predetermined frequency channels. Similarly, the subscribers transmit information back to the base station by broadcasting similar signals on one of the frequency channels. In this system, multiple users independently access the system through the

division of the frequency band into distinct subband frequency channels. This technique is known as frequency division multiple access (FDMA).

A standard technique used by commercial wireless phone systems to increasing capacity is to divide the service region into spatial cells, as shown in FIG. 2. Instead of using just one base station to serve all users in the region, a collection of base stations $B_1,\ldots,B_7$ are used to independently service separate spatial cells. In such a cellular system, multiple users can reuse the same frequency channel without interfering with each other, provided they access the system from different spatial cells. The cellular concept, therefore, is a simple type of spatial division multiple access (SDMA).

In the case of digital communication, additional techniques can be used to increase capacity. A few well known examples are time division multiple access (TDMA) and code division multiple access (CDMA). TDMA allows several users to share a single frequency channel by assigning their data to distinct time slots. CDMA is normally a spread-spectrum technique that does not limit individual signals to narrow frequency channels but spreads them throughout the frequency spectrum of the entire band. Signals sharing the band are distinguished by assigning them different orthogonal digital code sequences. These techniques use digital coding to make more efficient use of the available spectrum.

Wireless systems may also use combinations of the above techniques to increase capacity, e.g. FDMA/CDMA and TDMA/CDMA. Although these and other known techniques increase the capacity of wireless communication systems, there is still a need to further increase system performance. Recently, considerable attention has focused on ways to increasing capacity by further exploiting the spatial domain.

One well-known SDMA technique is to provide the base station with a set of independently controlled directional antennas, thereby dividing the cell into separate sectors, each controlled by a separate antenna. As a result, the frequency reuse in the system can be increased and/or cochannel interference can be reduced. Instead of independently controlled directional antennas, this technique can also be implemented with a coherently controlled antenna array, as shown in FIG. 3. Using a signal processor to control the relative phases of the signals applied to the antenna elements, predetermined beams can be formed in the directions of the separate sectors. Similar signal processing can be used to selectively receive signals only from within the distinct sectors.

In an environment containing a significant number of reflectors (such as buildings), a signal will often follow multiple paths. Because multipath reflections alter the signal directions, the cell space experiences angular mixing and can not be sharply divided into distinct sectors. Multipath can therefore cause cochannel interference between sectors, reducing the benefit of sectoring the cell. In addition, because the separate parts of such a multipath signal can arrive with different phases that destructively interfere, multipath can result in unpredictable signal fading.

In order to avoid the above problems with multipath, more sophisticated SDMA techniques have been proposed. For example, U.S. Pat. No. 5,471,647 and U.S. Pat. No. 5,634,199, both to Gerlach et al., and U.S. Pat. No. 5,592,490 to Barratt et al. disclose wireless communication systems that increase performance by exploiting the spatial domain. In the downlink, the base station determines the spatial channel of each subscriber and uses this channel information to adaptively control its antenna array to form customized beams, as shown in FIG. 4A. These beams transmit an information

signal x over multiple paths so that the signal x arrives to the subscriber with maximum strength. The beams can also be selected to direct nulls to other subscribers so that cochannel interference is reduced. In the uplink, as shown in FIG. 4B, the base station uses the channel information to spatially filter the received signals so that the transmitted signal x' is received with maximum sensitivity and distinguished from the signals transmitted by other subscribers. In this approach the same information signal follows several paths, providing increased spatial redundancy.

In the uplink, there are well known signal processing techniques for estimating the spatial channel from the signals received at the base station antenna array, e.g. by using *a priori* spatial or temporal structures present in the signal, or by blind adaptive estimation. If the uplink and downlink frequencies are the same, then the spatial channel for the downlink is directly related to the spatial channel for the uplink, and the base can use the known uplink channel information to perform transmit beamforming in the downlink. Because the spatial channel is frequency dependent and the uplink and downlink frequencies are often different, the base does not always have sufficient information to derive the downlink spatial channel information. One technique for obtaining downlink channel information is for the subscriber to periodically transmit test signals to the base on the downlink frequency rather than the uplink frequency. Another technique is for the base to transmit test signals and for the subscriber to feedback channel information to the base. If the spatial channel is quickly changing due to the relative movement of the base, the subscriber and/or reflectors in the environment, then the spatial channel must be updated frequently, placing a heavy demand on the system. One method to reduce the required feedback rates is to track only the subspace spanned by the time-averaged channel vector, rather than the instantaneous channel vector. Even with this

reduction, however, the required feedback rates are still a large fraction of the signal information rate.

Although these adaptive beamforming techniques require substantial signal processing and/or large feedback rates to determine the spatial channel in real time, these techniques have the advantage that they can navigate the complex spatial environment and avoid, to some extent, the problems introduced by multipath reflections. As a result, an increase in performance is enjoyed by adaptive antenna array systems, due to their use of the spatial dimension. Note, however, that while the base station antenna array can make efficient use of the spatial dimension by selectively directing the downlink signal to the subscriber S, the uplink signal in these systems is spatially inefficient. Typically, the subscriber is equipped with only a single antenna that radiates signal energy in all directions, potentially causing cochannel interference. These communication systems, therefore, do not make optimal use of the spatial dimension to increase capacity.

OBJECTS AND ADVANTAGES OF THE INVENTION

Accordingly, it is a primary object of the present invention to provide a communication system that significantly increases the capacity and performance of wireless communication systems by taking maximum advantage of the spatial domain. Another object of the invention is to provide computationally efficient coding techniques that make optimal use of the spatial dimensions of the channel. These and other objects and advantages will become apparent from the following description and associated drawings.

SUMMARY OF THE INVENTION

These objects and advantages are attained by a method of digital wireless communication that takes maximal advantage of spatial channel dimensions between a base station and a subscriber unit to increase system capacity and performance.

Surprisingly, the techniques of the present invention provide an increased information capacity in multipath environments. In contrast, known techniques suffer in the presence of multipath and do not exploit multipath to directly increase system capacity. In brief, the present invention teaches a method of wireless communication using antenna arrays at both the base and subscriber units to transmit distinct information signals over different spatial channels in parallel, thereby multiplying the capacity between the base and the subscriber. The present invention also teaches specific spatio-temporal coding techniques that make optimal use of these additional spatial subchannels.

Generally, the present invention provides a method of digital wireless communication between a base station and a subscriber unit, where a spatial channel characterized by a channel matrix **H** couples an array of M_T antenna elements at the base station with an array of M_R antenna elements at the subscriber unit. The method comprises the step of determining from the channel matrix **H** a number L of independent spatial subchannels, and encoding a plurality of information signals into a sequence of transmitted signal vectors. The transmitted signal vectors have M_T complex valued components and are selected to distribute distinct signal information over the independent spatial subchannels. The sequence of transmitted signal vectors is transmitted from the array of M_T antenna elements at the base station, and a sequence of received signal vectors is received at the array of M_R antenna elements at the subscriber unit. The received signal vectors have M_R complex valued components. These received signal vectors are decoded to yield the information signals.

In another aspect, the invention provides a method that comprises computing from a set of K original information signals a spatio-temporal coded signal in accordance with a channel matrix **H**. The channel matrix **H** represents the spatio-temporal characteristics of the information link between a

base station array of M_T antenna elements and a subscriber unit array of M_R antenna elements. Signal processing techniques are used to decompose $\mathbf{H}$ into K parallel spatio-temporal subchannels that can independently carry information signals between the base and subscriber units. After transmitting the spatio-temporal coded signal over the channel, it is decoded into a set of K received information signals that correspond to the K original information signals. In a preferred embodiment, the K parallel spatio-temporal subchannels are characterized by a set of K spatio-temporal transmission sequences that are derived from a decomposition of $\mathbf{H}$ into independent modes, and a set of K corresponding receive sequences. For example, the K spatio-temporal transmission sequences may be multiples of right singular vectors of $\mathbf{H}$, and the receive sequences may be a matched set of K spatio-temporal filter sequences that are left singular vectors of $\mathbf{H}$.

If L is the number of multipath components between the base station and the subscriber unit, then the number K of parallel spatio-temporal channels is not more than $(N+\nu) \times M_R$, not more than $N \times M_T$, and not more than $N \times L$, where $(N+\nu)$ is a maximum number of nonzero output samples transmitted for a block of N symbols. In a preferred embodiment, the original information signals comprise K blocks of N symbols, and the channel matrix $\mathbf{H}$ comprises $M_T \times M_R$ blocks of $N \times (N+\nu)$ channel matrices $\mathbf{H}_{ij}$.

In some applications of the present invention, the channel state information (CSI) may not be completely known, or may be expensive to compute. Accordingly, the present invention also provides a method for facilitating the efficient computation of the K received information signals from the transmitted spatio-temporal coded signal by adding cyclic prefixes to the coded signal prior to transmission.

DESCRIPTION OF THE FIGURES

FIG. 1 shows a low capacity wireless communication system well known in the prior art.

FIG. 2 illustrates a known technique of spatially dividing a service region into cells in order to increase system capacity.

FIG. 3 illustrates the use of beamforming with an antenna array to divide a cell into angular sectors, as is known in the art.

FIGS. 4A and 4B illustrate state-of-the-art techniques using adaptive antenna arrays for downlink and uplink beamforming, respectively.

FIGS. 5A and 5B show the parallel transmission of distinct information signals using spatial subchannels in downlink and uplink, respectively, as taught by the present invention.

FIGS. 6A and 6B are physical and schematic representations, respectively, of a communication channel for a system with multiple transmitting antennas and multiple receiving antennas, according to the present invention.

FIG. 7 is a block diagram of the system architecture for communicating information over a multiple-input-multiple-output spatial channel according to the present invention.

DETAILED DESCRIPTION

Although the following detailed description contains many specifics for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the following preferred embodiment of the invention is set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

As discussed above in relation to FIGS. 4A and 4B, prior art wireless systems employing an adaptive antenna array at the

base station are multiple-input-single-output (MISO) systems, i.e. the channel from the base to the subscriber is characterized by multiple inputs at the transmitting antenna array and a single output at the receiving subscriber antenna. Because these MISO systems can exploit some of the spatial channel, they have an increased capacity as compared to single-input-single-output (SISO) systems that are discussed above in relation to FIGS. 1 and 2. It should be noted that although the MISO systems disclosed in the prior art provide an increase in overall system capacity by spatially isolating separate subscribers from each other, these systems do not provide an increase in the capacity of information transmitted from the base to a single subscriber, or vice versa. As shown in FIGS. 4A and 4B, only one information signal is transmitted between the base and subscriber in both downlink and uplink of a MISO system. Even in the case where the subscriber is provided with an antenna array, the prior art suggests only that this capability would further reduce cochannel interference. Although the overall system capacity could be increased, this would not increase the capacity between the base and a single subscriber.

The present invention, in contrast, is a multiple-input-multiple-output (MIMO) wireless communication system that is distinguished by the fact that it increases the capacity of both uplink and downlink transmissions between a base and a subscriber through a novel use of additional spatial channel dimensions. The present inventors have recognized the possibility of exploiting multiple parallel spatial subchannels between a base station and a subscriber, thereby making use of additional spatial dimensions to increase the capacity of wireless communication. Surprisingly, this technique provides an increased information capacity and performance in multipath environments, a result that is in striking contrast with conventional wisdom.

FIGS. 5A and 5B illustrate a MIMO wireless communication system according to the present invention. As shown in FIG. 5A, a base station B uses adaptive antenna arrays and spatial processing to transmit distinct downlink signals x_1, x_2, x_3 through separate spatial subchannels to a subscriber unit S which uses an adaptive array and spatial processing to receive the separate signals. In a similar manner, the subscriber S uses an adaptive array to transmit distinct uplink signals x'_1, x'_2, x'_3 to the base B over the same spatial subchannels. As the multipath in the environment increases, the channel acquires a richer spatial structure that allows more subchannels to be used for increased capacity.

It is important to note that the simple assignment of the distinct signals to the distinct spatial paths in a one-to-one correspondence, as illustrated above, is only one possible way to exploit the additional capacity provided by the spatial subchannel structure. For example, coding techniques can be used to mix the signal information among the various paths. In addition, the present inventors have developed techniques for coupling these additional spatial dimensions to available temporal and/or frequency dimensions prior to transmission. Although such coupled spatio-temporal coding techniques are more subtle than direct spatial coding alone, they provide better system performance, as will be described in detail below.

In order to facilitate an understanding of the present invention and enable those skilled in the art to practice it, the following description includes a teaching of the general principles of the invention, as well as implementation details. First we develop a compact model for understanding frequency dispersive, spatially selective wireless MIMO channels. We then discuss their theoretical information capacity limits, and propose spatio-temporal coding structures that asymptotically achieve theoretical channel capacity. In particular, a spatio-temporal vector coding (STVC) structure

for burst transmission is disclosed, as well as a more practical, reduced complexity, discrete matrix multitone (DMMT) space-frequency coding structure. Both STVC and DMMT are shown to achieve the theoretical channel capacity as the burst duration increases.

In its preferred implementations, the present invention makes use of many techniques and devices well known in the art of adaptive antenna arrays systems and associated digital beamforming signal processing. These techniques and devices are described in detail in U.S. Pat. No. 5,471,647 and U.S. Pat. No. 5,634,199, both to Gerlach et al., and U.S. Pat. No. 5,592,490 to Barratt et al., which are all incorporated herein by reference. In addition, a comprehensive treatment of the present state of the art is given by John Livita and Titus Kwok-Yeung Lo in *Digital Beamforming in Wireless Communications* (Artech House Publishers, 1996). Accordingly, the following detailed description focuses upon the specific signal processing techniques which are required to enable those skilled in the art to practice the present invention.

Consider a communication channel for a system with M_T transmitting antennas at a base B and M_R receiving antennas at a subscriber S, as illustrated in FIGS. 6A and 6B. The channel input at a sample time k can be represented by an M_T dimensional column vector

$$\mathbf{z}(k) = [z_1(k), \ldots, z_{M_T}(k)]^T,$$

and the channel output and noise for sample k can be represented, respectively, by M_R dimensional column vectors

$$\mathbf{x}(k) = [x_1(k), \ldots, x_{M_R}(k)]^T,$$

and

$$\mathbf{n}(k) = [n_1(k), \ldots, n_{M_R}(k)]^T.$$

The communication over the channel $\mathbf{H}$ may then be expressed as a vector equation

$$\mathbf{x}(k) = \mathbf{H}\mathbf{z}(k) + \mathbf{n}(k),$$

where the MIMO channel matrix is

$$\mathbf{H} = \begin{pmatrix} h_{1,1} & \cdots & h_{1,M_T} \\ \vdots & & \vdots \\ h_{M_R,1} & \cdots & h_{M_R,M_T} \end{pmatrix}.$$

Each matrix element h_{ij} represents the SISO channel between the i^{th} receiver antenna and the j^{th} transmitter antenna. Due to the multipath structure of the spatial channel, orthogonal spatial subchannels can be determined by calculating the independent modes (e.g. eigenvectors) of the channel matrix $\mathbf{H}$. These spatial subchannels can then be used to transmit independent signals and increase the capacity of the communication link between the base B and the subscriber S. Because the multipath introduces time delays, however, a spatial decomposition alone will result in temporal mixing of the signals. It is more appropriate, therefore, to perform a more general spatio-temporal analysis of the channel.

Let $\{z_j(n)\}$ be a digital symbol sequence to be transmitted from the j^{th} antenna element, $g(t)$ a pulse shaping function impulse response, and T the symbol period. Then the signal applied to the j^{th} antenna element at time t is given by

$$s_j(t) = \sum_n z_j(n) g(t-nT)$$

The pulse shaping function is typically the convolution of two separate filters, one at the transmitter and one at the receiver. The optimum receiver filter is a matched filter. In practice, the pulse shape is windowed resulting in a finite duration impulse response. We assume synchronous complex baseband sampling with symbol period T. We define n_0 and $(v+1)$

to be the maximum lag and length over all paths l for the windowed pulse function sequences $\{g(nT-\tau_l)\}$. To simplify notation, it is assumed that $n_0 = 0$, and the discrete-time notation $g(nT-\tau_l) = g_l(n)$ is adopted.

When a block of N data symbols are transmitted, N+ν non-zero output samples result beginning at time sample k-N+1 and ending with sample k+ν. The composite channel output can now be written as an $M_R \aleph (N+\nu)$ dimensional column vector with all time samples for a given receive antenna appearing in order so that

$$\mathbf{x}(k) = [x_1(k-N+1),\ldots,x_1(k+\nu),\ldots,x_{M_R}(k-N+1),\ldots,x_{M_R}(k+\nu)]^T,$$

with an identical stacking for the output noise samples $\mathbf{n}(k)$. Similarly, the channel input is an $M_T \aleph N$ dimensional column vector written as

$$\mathbf{z}(k) = [z_1(k-N+1),\ldots,z_1(k),\ldots,z_{M_T}(k-N+1),\ldots,z_{M_T}(k)]^T,$$

The spatio-temporal communication over the channel $\mathbf{H}$ may then be expressed as a vector equation

$$\mathbf{x}(k) = \mathbf{H}\mathbf{z}(k) + \mathbf{n}(k),$$

where the MIMO channel matrix

$$\mathbf{H} = \begin{pmatrix} \mathbf{H}_{1,1} & \cdots & \mathbf{H}_{1,M_T} \\ \vdots & & \vdots \\ \mathbf{H}_{M_R,1} & \cdots & \mathbf{H}_{M_R,M_T} \end{pmatrix}$$

is composed of SISO sub-blocks $\mathbf{H}_{ij}$ with each sub-block possessing the well known Toeplitz form.

We will now discuss the information capacity for the spatio-temporal channel developed above. The following analysis assumes that the noise $\mathbf{n}(k)$ is additive white Gaussian noise (AWGN) with covariance $\sigma^2\mathbf{I}$. Each channel use consists of an N

symbol burst transmission and the total average power radiated from all antennas and all time samples is constrained to less than a constant.

Write the singular value decomposition (SVD) of the channel matrix as $\mathbf{H}=\mathbf{V}_H\Lambda_H\mathbf{U}_H^*$, with the j^{th} singular value denoted $\lambda_{H,j}$. Write the spatio-temporal covariance matrix for $\mathbf{z}(k)$ as $\mathbf{R}_Z$ with eigenvalue decomposition $\mathbf{R}_Z=\mathbf{V}_Z\Lambda_Z\mathbf{U}_Z^*$, and eigenvalues $\lambda_{Z,j}$.

It can be demonstrated that the information capacity for the discrete-time spatio-temporal communication channel defined above is given by

$$C = \sum_{n=1}^{N\aleph M_T} \log \left(1 + \frac{\lambda_{Z,n}|\lambda_{H,n}|^2}{\sigma^2}\right),$$

where $\lambda_{Z,n}$ is given by the spatio-temporal water-filling solution. Motivated by this result, the inventors devised the following temporal vector coding technique. By appropriately selecting up to $N\aleph M_T$ spatio-temporal transmission vectors that are multiples of the right singular vectors of $\mathbf{H}$, and receiving with up to $N\aleph M_T$ matched spatio-temporal filter vectors that are the left singular vectors of $\mathbf{H}$, up to $N\aleph M_T$ parallel spatio-temporal subchannels are constructed for communicating information over the channel. Mathematically, this STVC channel is derived as follows. Substituting $\mathbf{H}=\mathbf{V}_H\Lambda_H\mathbf{U}_H^*$ into the original equation $\mathbf{x}(k)=\mathbf{H}\mathbf{z}(k)+\mathbf{n}(k)$ for the channel gives

$$\mathbf{x}(k) = \mathbf{V}_H\Lambda_H\mathbf{U}_H^*\mathbf{z}(k) + \mathbf{n}(k),$$

Left multiplication by $\mathbf{V}_H^*$ yields

$$\mathbf{V}_H^*\mathbf{x}(k) = \Lambda_H\mathbf{U}_H^*\mathbf{z}(k) + \mathbf{V}_H^*\mathbf{n}(k),$$

which yields the STVC channel when rewritten as

$$\hat{\mathbf{x}}(k) = \Lambda_H \hat{\mathbf{z}}(k) + \hat{\mathbf{n}}(k),$$

where $\hat{\mathbf{z}}(k)=\mathbf{U}_H^* \mathbf{z}(k)$, $\hat{\mathbf{x}}(k)=\mathbf{V}_H^* \mathbf{x}(k)$ and $\hat{\mathbf{n}}(k)=\mathbf{V}_H^* \mathbf{n}(k)$.

By analyzing the ranks of the above matrices, it can be demonstrated that the maximum number of finite amplitude parallel spatio-temporal channel dimensions, K, that can be created to communicate over the far field channel defined above is equal to min { $N\aleph L$, $(N+\nu)\aleph M_R$, $N\aleph M$ }, where L is the number of multipath components. Thus, multipath is an advantage in far-field MIMO channels. If the multipath is large (L 1), the capacity can be multiplied by adding antennas to both sides of the radio link. This capacity improvement occurs with no penalty in average radiated power or frequency bandwidth because the number of parallel channel dimensions is increased. In practice, an adaptive antenna array base station, such as that described by Barratt et al., is modified to implement the above vector coding scheme. In particular, a signal processor is designed to perform a spatio-temporal transform of information signals in accordance with the above equations so that they may be transmitted through the independent parallel subchannels and decoded by the subscriber.

The space-time vector coding solution described above requires a computation of the singular value decomposition of an $(N+\nu)\aleph M_R \times N\aleph M_T$ matrix. Since this computation can be complex, the present inventors have developed an optimal space-time communication structure that requires less computational complexity to implement. In particular, complexity can be reduced by using a coding structure similar to the discrete multi-tone (DMT) standard. DMT is in widespread use for wired SISO channels. DMT has also been applied to wired MISO channels, as described in U.S. Pat. No. 5,625,651 which is hereby incorporated by reference. The present inventors have generalized DMT to the MIMO case and

adapted it to wireless channels to obtain a novel space-frequency coding structure that results in a matrix of transmission and reception vector solutions for each discrete Fourier transform (DFT) frequency index. Because this new coding scheme has been generalized to MIMO channels characterized by a channel matrix, it is called discrete matrix multi-tone (DMMT).

In DMMT, N data symbols are again transmitted during each channel usage. However, a cyclic prefix is added to the data so that the last ν data symbols are transmitted from each antenna element prior to transmitting the full block of N symbols. By receiving only N time samples at the output of each antenna element, ignoring the first and last ν output samples, the MIMO channel submatrices $\hat{\mathbf{H}}_{ij}$ now appear as cyclic structures:

$$\hat{\mathbf{H}}_{i,j} = \begin{pmatrix} h(\nu) & \cdots & h(0) & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & h(\nu) & & h(0) & 0 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & & & & \vdots & & \vdots & & & \vdots \\ 0 & & & & 0 & \cdots & 0 & & & 0 \\ 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & h(\nu) & \cdots & h(0) \\ & & & \vdots & \vdots & & \vdots & & & \vdots \\ h(\nu-1) & \cdots & h(0) & 0 & 0 & \cdots & 0 & \cdots & 0 & h(\nu) \end{pmatrix}$$

Given the cyclic SISO channel blocks, the channel matrix can be diagonalized with a relatively simple three step procedure. First post multiply $\hat{\mathbf{H}}$ with the $N \times M_T \times N \times M_T$ block diagonal inverse discrete Fourier transform (IDFT) matrix $\mathbf{F}^{*(M_T)}$ where each diagonal block is the unitary $N \times N$ IDFT matrix $\mathbf{F}^*$. The next step is to premultiply $\hat{\mathbf{H}}$ by a similar $N \times M_R \times N \times M_R$ block diagonal DFT matrix $\mathbf{F}^{(M_R)}$ where the diagonal submatrices $\mathbf{F}$ are $N \times N$ DFT matrices. With the well known result that the discrete Fourier transform basis vectors form the orthonormal singular vectors of the cyclic matrices $\hat{\mathbf{H}}_{ij}$, the new channel

matrix resulting from the IDFT post multiplication and the DFT premultiplication is

$$\mathbf{F}^{(M_R)}\hat{\mathbf{H}}\mathbf{F}^{*(M_T)} = \begin{pmatrix} \Gamma_{1,1} & \cdots & \Gamma_{1,M_T} \\ \vdots & & \vdots \\ \Gamma_{M_R,1} & \cdots & \Gamma_{M_R,M_T} \end{pmatrix}$$

where $\Gamma_{i,j}$ is the diagonal matrix containing the singular values $\gamma_{i,j,n}$ of the cyclic channel submatrix $\hat{\mathbf{H}}_{ij}$. Premultiplication and postmultiplication by a permutation matrix $\mathbf{P}$ yields the block diagonal matrix

$$\mathbf{P}\mathbf{F}^{(M_R)}\hat{\mathbf{H}}\mathbf{F}^{*(M_T)}\mathbf{P} = \begin{pmatrix} \mathbf{B}_1 & & 0 \\ & \ddots & \\ 0 & & \mathbf{B}_N \end{pmatrix}$$

where

$$\mathbf{B}_n = \begin{pmatrix} \gamma_{1,1,n} & \cdots & \gamma_{1,M_T,n} \\ \vdots & & \vdots \\ \gamma_{M_R,1,n} & \cdots & \gamma_{M_R,M_T,n} \end{pmatrix}$$

is the $M_R \times M_T$ space-frequency channel evaluated at DFT index n. Given the SVD of $\mathbf{B}_n = \mathbf{V}_{B,n}\Lambda_{B,n}\mathbf{U}^*_{B,n}$, the diagonal DMMT channel matrix $\hat{\mathbf{H}}$ is finally obtained by post multiplying by $\mathbf{U}_B^{(M_T)}$ and premultiplying by $\mathbf{V}_B^{*(M_R)}$ to obtain

$$\Lambda_{\hat{H}} = \mathbf{V}_B^{*(M_R)}\mathbf{P}\mathbf{F}^{(M_R)}\hat{\mathbf{H}}\mathbf{F}^{*(M_T)}\mathbf{P}\mathbf{U}_B^{(M_T)} = \begin{pmatrix} \Lambda_{\hat{H},1} & & 0 \\ & \ddots & \\ 0 & & \Lambda_{\hat{H},N} \end{pmatrix}$$

where $\mathbf{U}_B^{(M_T)}$ is block diagonal containing the right singular matrices of the $\mathbf{B}_n$ matrices, $\mathbf{V}_B^{*(M_R)}$ is block diagonal containing the left singular matrices of the $\mathbf{B}_n$ matrices, and each of the diagonal submatrices $\Lambda_{\hat{H},n}$ contains the DMMT spatial sub-channel amplitudes, $\lambda_{\hat{H},n,j}$ for DFT bin n. The parallel channel DMMT equation is then

$$\hat{\mathbf{x}}(k) = \Lambda_{\hat{H}}\hat{\mathbf{z}}(k) + \hat{\mathbf{n}}(k),$$

where $\mathbf{z}(k)$ is the dimension $N\aleph M_T$ input symbol vector, $\hat{\mathbf{x}}(k)$ is the dimension $N\aleph M_R$ output symbol vector, and $\hat{\mathbf{n}}(k)$ is the dimension $N\aleph M_R$ equivalent output noise vector after the DFT and spatial orthogonalization operations are performed. A block diagram architecture that implements this DMMT space-frequency channel decomposition is presented in FIG. 7. The left portion of the diagram corresponds to the application of the operators $\mathbf{F}^{*(M_T)}\mathbf{P}\mathbf{U}_B^{(M_T)}$ on the signal $\hat{\mathbf{z}}(k)$. These operations are performed by a signal processor at the transmitter. The right portion of the diagram corresponds to the application of the operators $\mathbf{V}_B^{*(M_R)}\mathbf{P}\mathbf{F}^{(M_R)}$ on the received signals to recover a received information signal $\hat{\mathbf{x}}(k)$. These operations are performed by a signal processor at the receiver. The central matrix $\hat{\mathbf{H}}$ corresponds to the spatial channel itself. By construction, the signal processing operations result in a direct relationship between the received and transmitted information signals, as indicated by the fact that the matrix $\Lambda_{\hat{H}}$ in the parallel channel DMMT equation is diagonal.

This coding scheme significantly reduces the signal processing complexity required at the transmitter and receiver to diagonalize all space-time subchannels for each data block. In particular, this asymptotically optimal space-frequency MIMO DMMT information transmission technique has a complexity advantage of approximately N^2 as compared to the vector coding case. Moreover, since all of the matrix operations involved in creating the diagonal DMMT channel are invertible, the capacity of the DMMT channel is unchanged from that of the original cyclic sub-block matrix $\hat{\mathbf{H}}$. Thus, compared to STVC, the only capacity decrease for the DMMT space-time coding solution is due to the radiated power penalty required to transmit the cyclic prefix. This capacity penalty, however,

becomes small for large N. Thus, this new communications structure offers the advantage of very large increases in capacity without penalty in total average transmitted power or bandwidth.

In order to perform transmit beamforming, the base station signal processor computes spatio-temporal downlink subchannel information from downlink channel information fed back from the subscriber. The downlink signal information is then encoded in accordance with this computed downlink subchannel information. Similarly, the subscriber performs the same functions for the uplink channel using information fed back from the base. Because the present invention provides techniques for efficient channel estimation and increased channel capacity, the base and subscriber can both quickly estimate the channel and exchange channel information over the increased capacity channels, possibly at a rate slower than that of information data. As a result, both the base and subscriber can maintain a high degree of spatial resolution in transmit beamforming, thereby significantly reducing cochannel interference from other base stations or subscribers. As a result of this high degree of spatial discrimination in both transmission and reception, many more base stations and subscribers can share the same region of space while using the same frequency channel. Consequently, in addition to increasing the capacity of the channel between any two arrays, the present invention also increases system wide capacity by significantly reducing cochannel interference.

The teaching contained in this description can easily be extended to channels where the noise is not white but is highly structured as in the case of additive co-channel interference. In this case, large gains in cellular network capacity result from the ability to null interference at the receiver and the ability to constrain radiated interference power at the transmitter. These spatial coding techniques can also be applied to single frequency subchannel systems with

flat fading, conventional analog multicarrier transmission channels, or CDMA channels where each code delay can be decomposed into orthogonal subchannels provided that there is sub-chip multipath. The concepts of the present invention can also be applied to a more general class of channels where the antenna array is distributed over large distances and the propagation does not follow far field behavior. Finally, other communication media such as wire-line, acoustic media, and optical media will experience the same basic communication system benefits when spatio-temporal MIMO channel structures are employed. Thus, it will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.

CLAIMS

What is claimed is:

1. A method of digital wireless communication between a base station and a subscriber unit, the method comprising:

determining from channel information a number L of independent spatial subchannels, wherein the channel information comprises spatial information relating to a spatial channel coupling an array of M_T antenna elements at the base station with an array of M_R antenna elements at the subscriber unit;

encoding a plurality of information signals into a sequence of transmitted signal vectors, wherein the transmitted signal vectors have M_T complex valued components and are selected to send distinct information signal over the independent spatial subchannels;

transmitting the sequence of transmitted signal vectors from the array of M_T antenna elements at the base station;

receiving a sequence of received signal vectors at the array of M_R antenna elements at the subscriber unit, wherein the received signal vectors have M_R complex valued components; and

decoding the received signal vectors to recover the information signals.

2. The method of claim 1 further comprising transmitting the channel information from the subscriber to the base.

3. The method of claim 1 wherein the channel information comprises a spatio-temporal channel matrix.

4. The method of claim 1 wherein the number L of independent spatial subchannels is equal to the number of multiple signal paths between the base and the subscriber.

5. The method of claim 1 wherein the encoding step comprises scaling the information signals by complex numbers,

permuting the scaled information signals and inverse Fourier transforming the permuted scaled information signals, and wherein the decoding step comprises Fourier transforming the received signals, permuting the Fourier transformed received signals, and scaling the permuted Fourier transformed received signals.

6. A method of digital wireless communication between a base station and a subscriber unit, the method comprising:
computing from a set of K original information signals a spatio-temporal coded signal in accordance with a channel matrix **H** having K parallel spatio-temporal subchannels;
transmitting the spatio-temporal coded signal from a base station array of M_T antenna elements through a channel corresponding to the channel matrix **H** to a subscriber unit array of M_R antenna elements; and
computing from the transmitted spatio-temporal coded signal a set of K received information signals.

7. The method of claim 6 wherein K is not more than $(N+v) \times M_R$, not more than $N \times M_T$, and not more than $N \times L$, where L is a maximum number of multipath components between the base station and the subscriber unit, and where $(N+v)$ is a maximum number of nonzero output samples transmitted for a block of N symbols.

8. The method of claim 6 wherein the original information signals comprise K blocks of N symbols, and the channel matrix **H** comprises $M_T \times M_R$ blocks of $N \times (N+v)$ channel matrices $\mathbf{H}_{ij}$, where $(N+v)$ is a maximum number of nonzero output samples transmitted for a block of N symbols.

9. The method of claim 6 wherein cyclic prefixes are added to the coded signal prior to the transmitting step, thereby facilitating the efficient computation of the K received information signals from the transmitted spatio-temporal coded signal.

10. The method of claim 6 wherein the K parallel spatio-temporal subchannels are characterized by a set of K spatio-temporal transmission sequences that are derived from a decomposition of **H** into independent modes.

11. The method of claim 6 wherein the K parallel spatio-temporal subchannels are characterized by a set of K spatio-temporal transmission sequences that are multiples of right singular vectors of **H**, and matched set of K spatio-temporal filter sequences that are left singular vectors of **H**.

12. A digital wireless communication system comprising:

a base station comprising a base station antenna array and a base station signal processor coupled to the base station antenna array;

a subscriber unit comprising a subscriber antenna array coupled through a wireless channel to the base station antenna array and a subscriber signal processor coupled to the subscriber antenna array;

wherein the base station signal processor computes spatio-temporal downlink subchannel information from downlink channel information received from the subscriber, and encodes downlink signal information in accordance with the computed downlink subchannel information; and

wherein the subscriber signal processor computes spatio-temporal uplink subchannel information from uplink channel information received from the base station, and encodes uplink signal information in accordance with the computed uplink subchannel information.

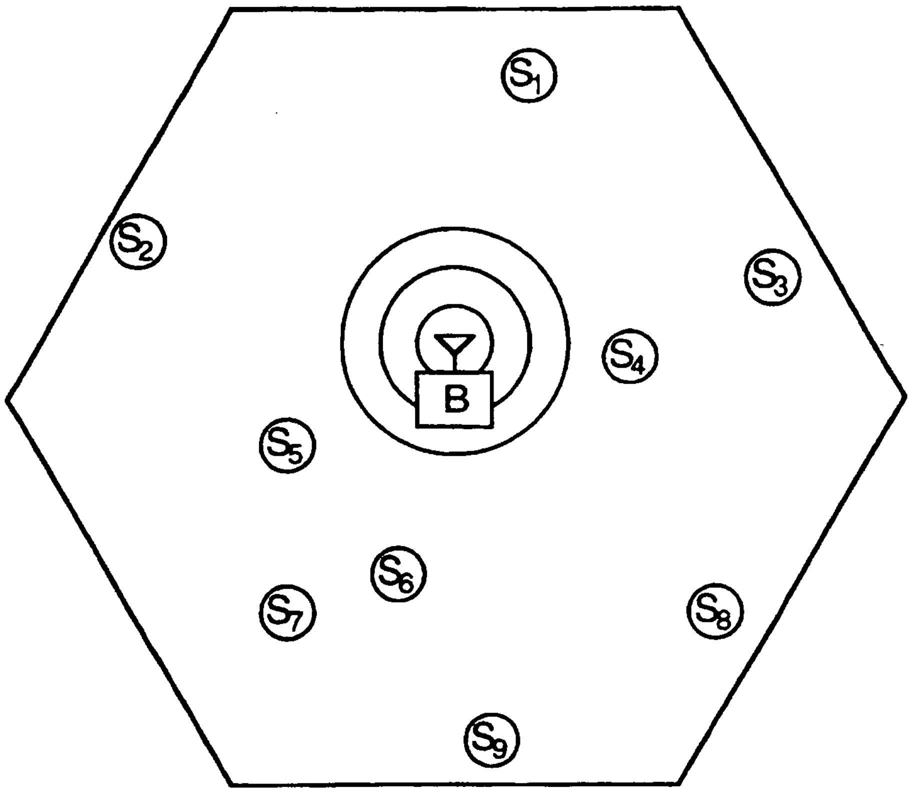


FIG. 1
(PRIOR ART)

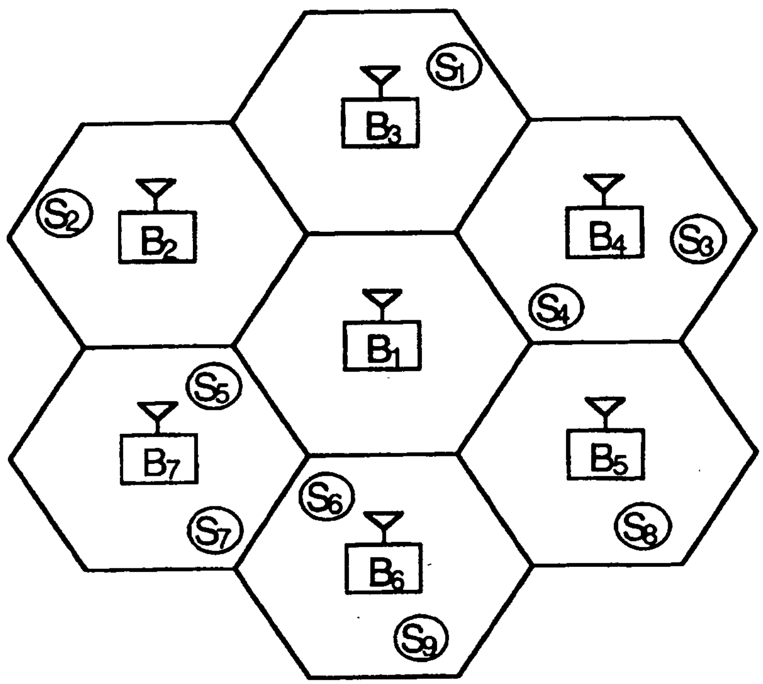


FIG. 2
(PRIOR ART)

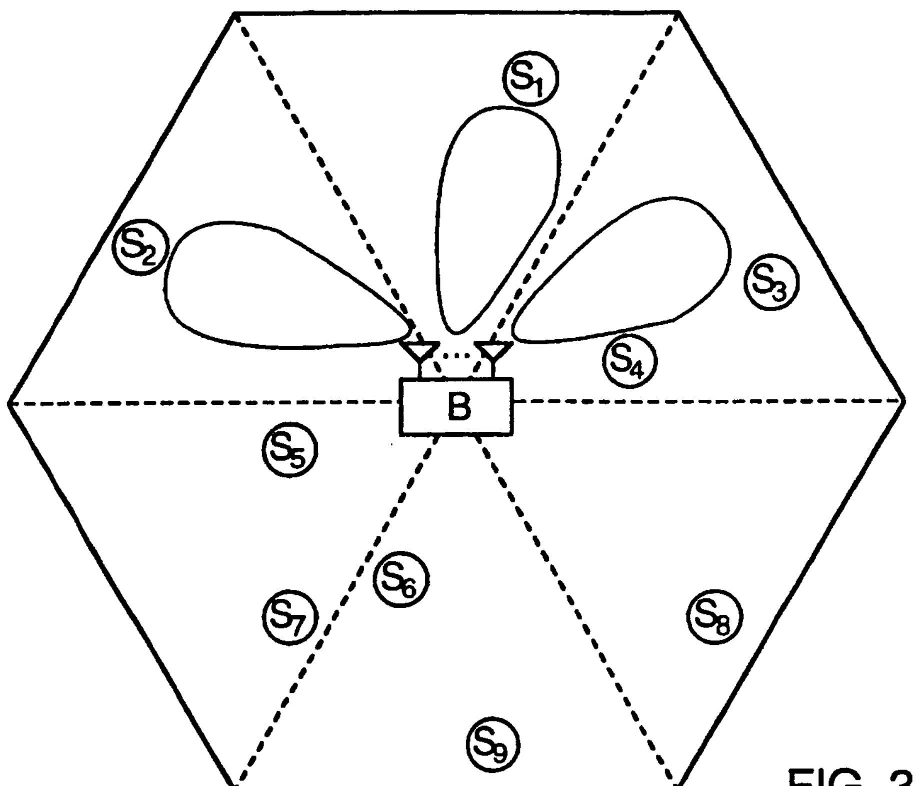


FIG. 3
(PRIOR ART)

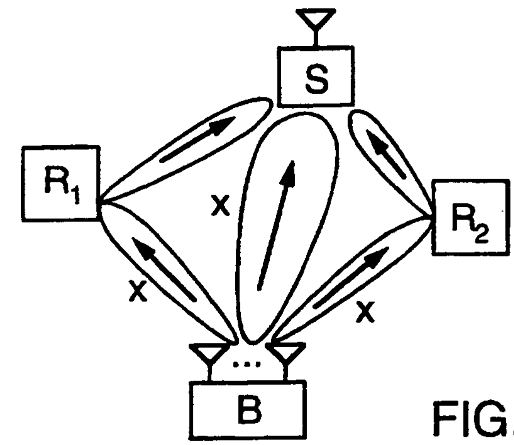


FIG. 4A
(PRIOR ART)

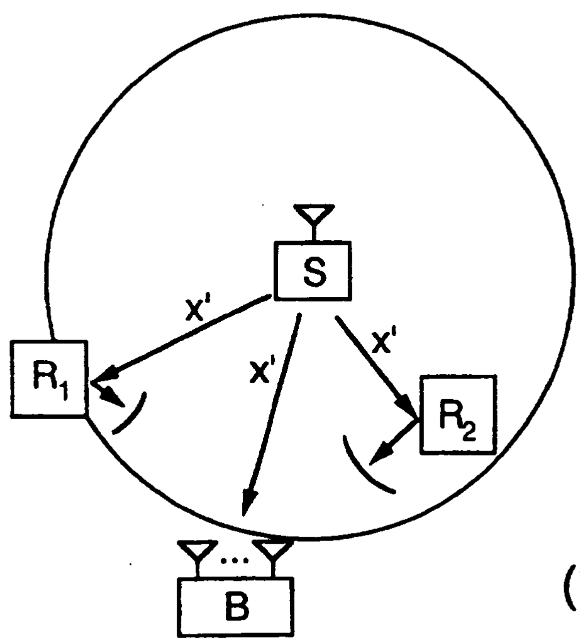


FIG. 4B
(PRIOR ART)

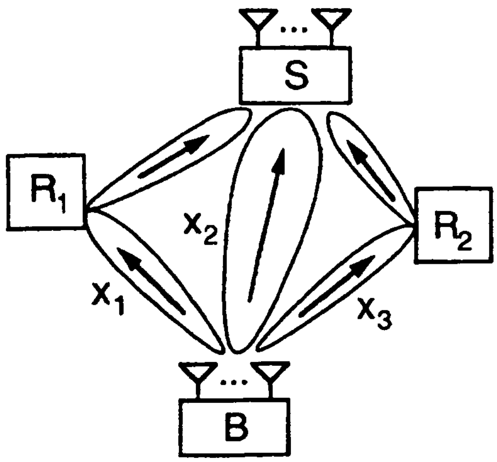


FIG. 5A

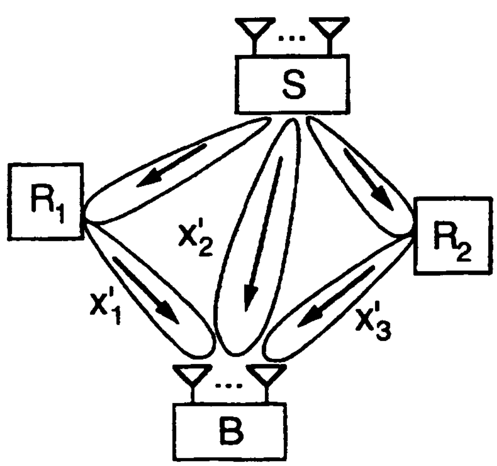
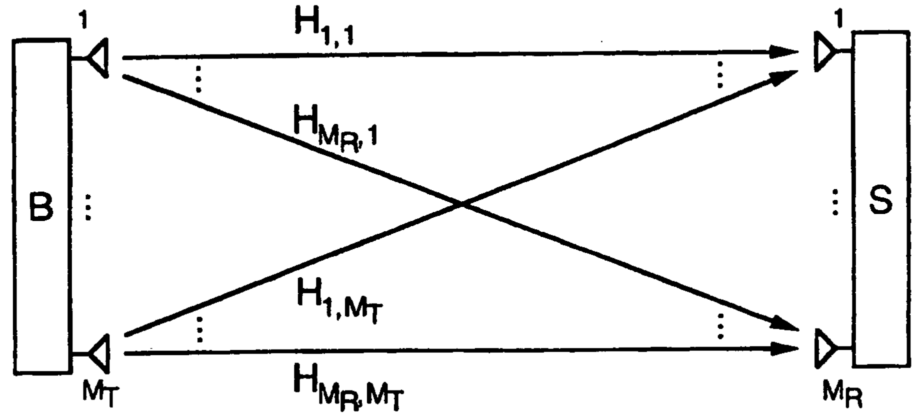
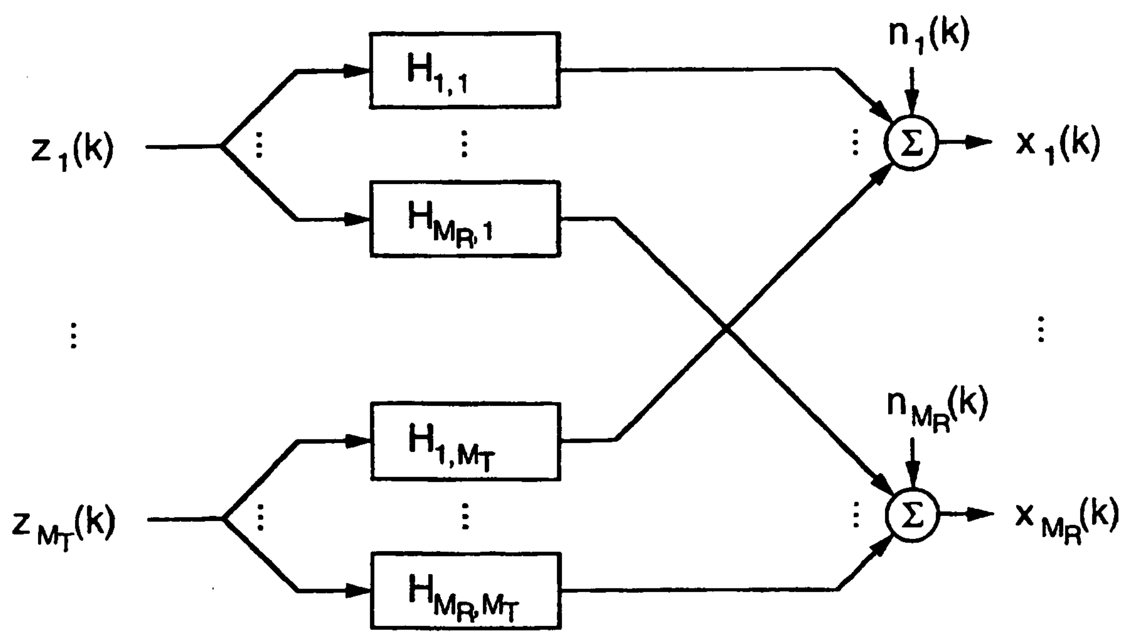


FIG. 5B



1
1
B
S
$H_{1,1}$
$H_{M_R,1}$
H_{1,M_T}
H_{M_R,M_T}
M_T
M_R

FIG. 6A



$z_1(k)$
$z_{M_T}(k)$
$H_{1,1}$
$H_{M_R,1}$
H_{1,M_T}
H_{M_R,M_T}
$n_1(k)$
$n_{M_R}(k)$
Σ
Σ
$x_1(k)$
$x_{M_R}(k)$

FIG. 6B

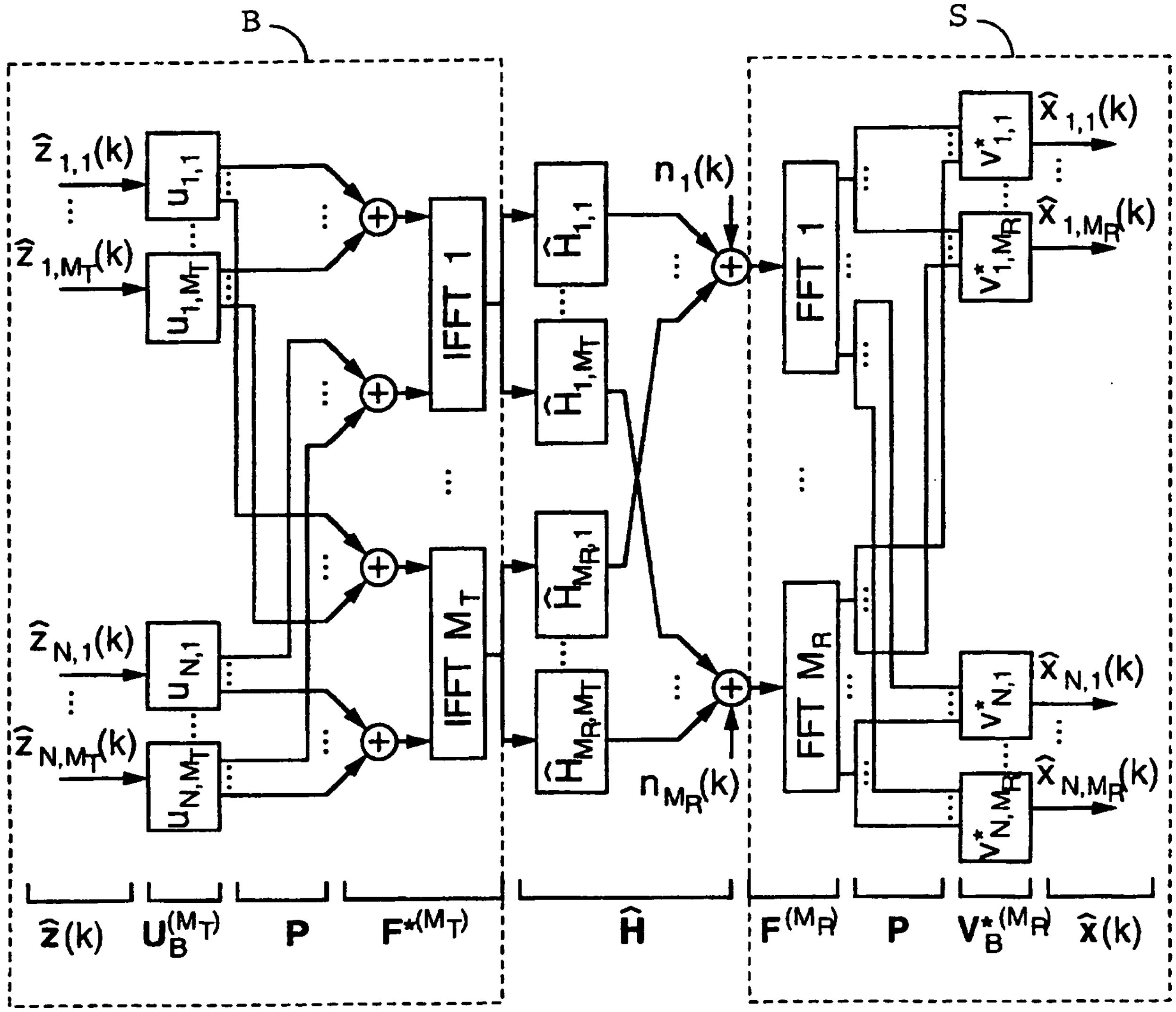

B
S
$\hat{z}_{1,1}(k)$
$\hat{z}_{1,M_T}(k)$
$\hat{z}_{N,1}(k)$
$\hat{z}_{N,M_T}(k)$
$u_{1,1}$
u_{1,M_T}
$u_{N,1}$
u_{N,M_T}
IFFT 1
IFFT M_T
$\hat{H}_{1,1}$
$\hat{H}_{1,M_T}$
$\hat{H}_{M_R,1}$
$\hat{H}_{M_R,M_T}$
$n_1(k)$
$n_{M_R}(k)$
FFT 1
FFT M_R
$V^*_{1,1}$
V^*_{1,M_R}
$V^*_{N,1}$
V^*_{N,M_R}
$\hat{x}_{1,1}(k)$
$\hat{x}_{1,M_R}(k)$
$\hat{x}_{N,1}(k)$
$\hat{x}_{N,M_R}(k)$
$\hat{\mathbf{z}}(k)$
$\mathbf{U}_B^{(M_T)}$
$\mathbf{P}$
$\mathbf{F}^{*(M_T)}$
$\hat{\mathbf{H}}$
$\mathbf{F}^{(M_R)}$
$\mathbf{P}$
$\mathbf{V}_B^{*(M_R)}$
$\hat{\mathbf{x}}(k)$

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/15363

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H04B 1/38; H04M 1/00
US CL :455/562, 101, 103, 272
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 455/562, 101, 103, 272, 504, 506, 65, 132; 375/347

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4,710,944 A (NOSSEN) 01 December 1987, columns 3-8, figures 1 and 5.	1-12
X	US 5,548,819 A (ROBB) 20 August 1996, columns 10-13, figures 1a-1b.	1-12
A,P	US 5,649,287 A (FORSSEN ET AL) 15 July 1997, figure 5.	1-12

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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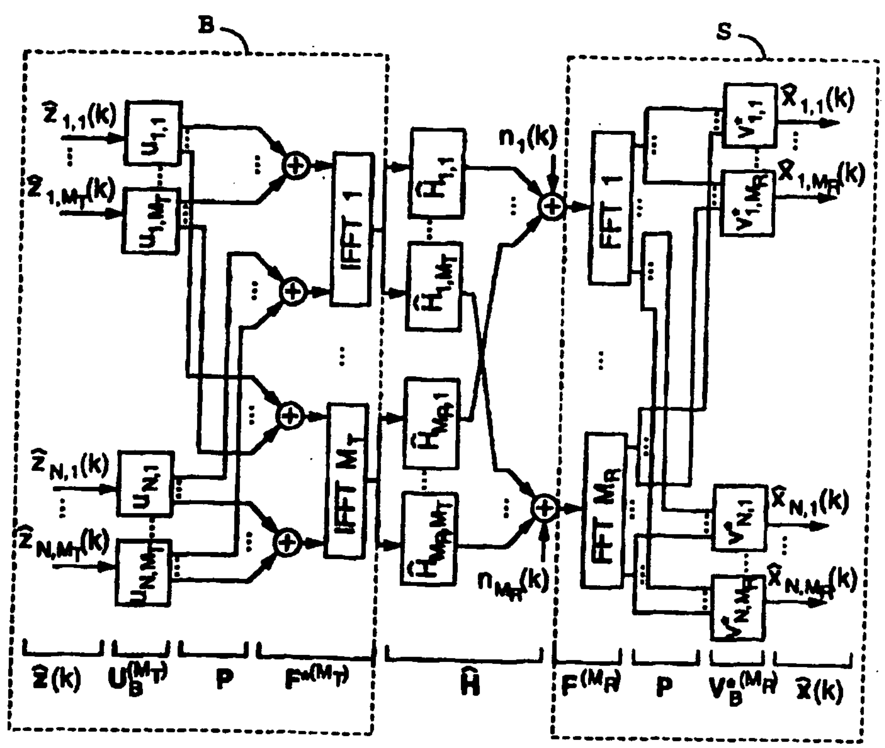
(54) Title: HIGH CAPACITY WIRELESS COMMUNICATION USING SPATIAL SUBCHANNELS

(57) Abstract



In a system and method of digital wireless communication between a base station (B) and a subscriber unit (S), a spatial channel characterized by a channel matrix H couples an adaptive array of Mt antenna elements (1-Mt) at the base station (B) with an adaptive array Mr antenna elements (1-Mr) at the subscriber unit (S). The method comprises the step of determining from the channel matrix H a number L of independent spatio-temporal subchannels, and encoding a plurality of information signals into a sequence of transmitted signal vectors. The transmitted signal vectors have Mt complex valued components and are selected to transmit distinct signal information in parallel over the independent subchannels, thereby providing increased communication capacity between the base and the subscriber. The sequence of transmitted signal vectors is transmitted from the base station array (1-Mt), and a sequence of received signal vectors is received at the subscriber array (1-Mr) and are decoded to yield the original information signals. Specific spatio-temporal coding techniques are described that increase system performance.

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